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UNDERGROUND FLOW IN CAVERNOUS LIMESTONES WITH SPECIAL REFERENCE TO THE MALHAM AREA

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ABSTRACT

THE paper consists of four parts. An outline is given of the flow of water in cavernous limestones and the information that can be obtained by a variety of water tracing techniques. Secondly, a review is given of the nineteenth-century water tracing that was undertaken in the Malham area. Thirdly, water tracing experiments undertaken in 1972 and 1973 are described. The methods included the use of fluorescent dyes, *Lycopodium* spores and flood pulses. The results of these experiments, which are discussed in the fourth section, extend the findings of the earlier work.

It is shown that the water from Water Sinks flows via subterranean conduits in the Carboniferous Limestone to emerge at both the Airehead and Malham Cove springs. Normally, only a small proportion of the stream flows to Malham Cove, the majority feeding Airehead. By considering the behaviour of tracer dyes and water pulses released from Malham Tarn, within the underground system, it is deduced that the stream passes to the Airehead Springs through a network of largely water-filled conduits under turbulent flow conditions, and that a greater proportion of the network is actively swept out by the stream as the total discharge increases. It is also shown that a smaller stream sinking at Smelt Mill feeds the Malham Cove spring, a result which confirms earlier work, although in the recent experiments tracers from Smelt Mill were also recovered at Airehead.

1. UNDERGROUND FLOW IN CAVERNOUS LIMESTONES

Limestone landscapes have little surface drainage except under special circumstances where subterranean drainage is prevented by the occurrence of permafrost. The relationship of limestone hydrology to landform is close, as much of the erosion of the limestone is due to solution. Thus, how the water flows on or through the limestone will control the sites at which the erosion by solution is concentrated. If the underground drainage is dominated by movement along a limited number of major flow paths the solutional erosion will be similarly concentrated. Conversely, if the flow is via a multitude of minor paths the erosion is disseminated throughout the whole limestone mass. Thus an understanding of the hydrology is likely to be of importance in extending our knowledge of limestone landforms. Such studies are also significant for applied purposes in that they are useful in the management of water resources particularly in the fields of water supply and waste disposal.

If it is accepted that the type of underground flow is important in the study of limestone geomorphology, it is necessary to classify limestones according to their hydrological properties. Some limestone areas contain well-developed caves, and these form a clear example of a subterranean network of flow paths with a low drainage density, although each path or cave is capable of carrying a large discharge. The major caving regions of the United Kingdom are all of this type and all are located in limestones of Carboniferous age. The Chalk landscape of Britain has few caves; by inference it may be considered to have a far higher density of flow paths but with each part of the network having much smaller dimensions than in the Carboniferous Limestone. The geomorphology of both these limestones is dominated by solutional erosion, and in broad terms the rate of removal of limestone is similar although solution occurs at different sites.

1. 1: *Subterranean Flow in Limestones*

At this stage it is necessary to introduce a limited number of terms and definitions. Workers in this field have generally accepted the terms *conduit* and *diffuse* flow, proposed by White (1969), to describe the two dominant forms of water movement in limestones. Conduit flow can be considered as similar in form to flow in surface streams. The velocity of flow is considerable and is often in excess of several centimetres per second (i.e. several km/day) and the flow form is turbulent. This has important consequences in that turbulent flow can carry a considerable load of particulate material either in suspension or as traction (bed) load. This transported material causes erosion by abrasion in addition to solutional effects. The pattern of underground drainage exhibits a network comparable to that of surface streams although clearly more complex owing to the three dimensional nature of the network. A normal cave passage would be an example of such a conduit, but it is important to realize that conduit flow can occur in passages with cross sectional dimensions of less than a centimetre and in passages which are completely water filled even at periods of low discharge. Thus the term "cavernous" describes a limestone where the dominant flow form is turbulent in conduits with a low degree of interconnection.

Conversely, diffuse flow normally occurs along flow paths that are of very small cross sectional dimensions, measured in fractions of a millimetre, and having a high degree of interconnectivity. The velocity is often extremely low, perhaps measured in metres per year, and flow is mainly laminar. A laminar regime does not permit the transport of particulate material, and the solutional erosion will be distributed within the rock mass in a pattern very different to that found with conduit flow.

Diffuse and conduit flow are two end members of a continuous series. Both frequently occur within the same limestone mass but are rarely of exactly equal importance. As a stream network evolves on a limestone surface the initial subterranean flow is likely to be of the diffuse, laminar type. Then, as individual flow lines become enlarged by solution turbulent flow begins. The underground flow paths then develop more rapidly, conduit flow gradually becomes dominant and surface drainage is frequently entirely captured by the underground flow. Theoretically, given sufficient time, all limestones would develop some conduit drainage, because at least a few flow paths would become sufficiently enlarged by solution for turbulent flow to begin.

1.2: *The Concepts of Porosity, Permeability and the Water Table*

Linked with the concepts of diffuse and conduit flow are the terms *permeability* and *porosity*. Permeability (or hydraulic conductivity) is a measure of the rate at which water is transmitted through a rock and is commonly expressed in terms of metres per day. Porosity is a measure of the void space within a rock and is usually given as the percentage voids. It is possible to undertake relatively simple laboratory tests on small rock specimens to determine their permeability and porosity. Laboratory permeability values typical of the Carboniferous limestones are often less than 0·01 m/day. They are thought to reflect the permeability of the inter-granular pores of the rock, and are therefore referred to as *primary* permeability, in contrast to the *secondary* permeability which is due to water movement along joints, bedding planes and other fractures, or along solutionally enlarged conduits. Values for secondary permeability and porosity can only be determined in the field.

For cavernous limestones, of which the Carboniferous Limestone of the Malham area is an example, the values for primary permeability and secondary permeability are very different. An extreme example would be an area of limestone pavement composed of limestone blocks, the clints, separated by the solutionally opened grikes. The permeability obtained from rock specimens from the clints would be very low. However, the drainage of water through the grikes would give the whole limestone mass a very high secondary permeability. Thus cavernous limestones are distinguished by a dominance of secondary permeability which has been greatly enhanced by the solutional widening of joints, etc., to form conduits.

The final term to be considered is the *water table.* In its simplest form the water table is a subterranean surface below which the voids of the rock are entirely filled with water. Above the water table the voids also contain air, and the water in them is flowing downwards under gravity. Water flow above the water table is termed *vadose*, and below it, *phreatic.* Interconnected voids in the phreatic zone are water-filled and in most rocks the water movement is slow and likely to be laminar. Its direction follows the steepest slope of the water table. In non-limestones flow in the vadose zone is sometimes rapid and very occasionally turbulent. The vadose zone in limestones includes rapid, turbulent flow in the potholes and streamways typical of the caves of north-west Yorkshire, as well as the slower flow of trickles down solutionally-widened joints or grikes and the diffuse flow of water down narrower fractures.

If a bore hole is sunk below the water table in alluvium or unconsolidated sands the rest level of the water approximates to the water table and it is possible to calculate the permeability by means of a pumping test. Pumping tests methods assume that the water movement in the phreatic zone is laminar and evenly distributed throughout the whole of the rock volume. This is certainly the case in granular media such as sand and it seems to apply also to a wide variety of closely fractured rocks. To a large extent this is also the case in closely fractured non-cavernous limestones of which the Chalk of southern England is an example. However, turbulent conduit flow does occur locally in the Chalk and a specific example is discussed in Atkinson and Smith (1974).

The validity of the water table concept in cavernous limestones is a topic of long-standing debate. It is possible to recognize three schools of thought. The first maintains that there is indeed a continuous water table present and that cavern or conduit development is closely controlled by its regional slope. Proponents of this view include Grund (1903), Davis (1930) and Swinnerton (1932). The opposing school, e.g. Katzer (1909), Zötl (1965) and Drew (1966), maintain that the water table model is irrelevant as the bulk of the groundwater flow is through conduits which bear no relation to the water table which preceded them and which have developed along the widest fractures which were initially present in the rock. A further group of workers consider that a model based upon a discontinuous water table present only in the larger openings and conduits is the most useful concept. Cvijic (1918) was the first proponent of this view and Thrailkill (1968), in an excellent review of the whole question, may also be placed in this group.

The ideas of diffuse and conduit flow, primary and secondary permeability and the validity of the water table model are all intimately linked with a study of the hydrology and geomorphology of cavernous limestones. It is difficult to obtain field data to investigate these concepts in an individual area of limestone. It is certain that the hydrological properties will vary from area to area and among limestones of different lithology. These variations are also likely to play an important role in determining the overall geomorphology.

The early work on underground flow in cavernous limestones was mainly based upon the pattern and morphology of caves. Over the last twenty years or so, two additional lines of evidence have been added. These are the solute contents of the waters in limestone terrains, and a variety of water tracing techniques which have been applied to the subterranean flow. This account is concerned with the application of tracer techniques to cavernous limestones.

1.3: *Evidence provided by water tracing*

Water tracing for scientific and applied research has made considerable progress in recent years, but the principles are similar to those used in earlier studies. Normally, the objective is to trace water disappearing from a surface stream, or "sink", to a nearby spring. A variety of tracers have been used and they are divisible into four groups. The most widely used are particulate and chemical tracers but more recently radioactive and bacteriological methods have also been used. A broad review and bibliography are given in Smith (1977, *in press*). The studies described later use a particulate method, with *Lycopodium* spores as the tracer, and a chemical method with fluorescent dyestuffs.

The first method involves introducing the naturally occurring spores of a club-moss, *Lycopodium clavatum*, into the sinking streams. The spores are cellulose-walled sub-spherical particles about 25 micrometres in diameter and slightly denser than water. Although they will settle out in completely still water, very slight turbulence is sufficient to keep them in suspension and they are therefore ideal tracers for underground streams in limestone areas (Drew and Smith, 1969; Atkinson *et al.*, 1973). The spores may be dyed in up to five different colours, making possible the simultaneous tracing of five streams. They are detected at springs by filtering part of the flow through conical plankton nets and collecting samples of the filtered sediment for examination under a microscope. A natural application was to attempt tracing from multiple inputs and to monitor springs over a wide area. This work was pioneered by Zötl and his co-workers (see Maurin and Zötl, 1959) in Austria. The method has an additional advantage in that the nets at the springs filter out spores over a considerable period of time and thus the chances of missing the tracer output are very much reduced. The method was later used extensively in the Mendip Hills (see Smith and Drew, 1975), and in such diverse limestone terrains as Yugoslavia and Jamaica. The major conclusions to be drawn from these studies were:

(i) If the work is carefully undertaken the majority of stream sinks can be shown to connect with spring sources.

(ii) Some but by no means all individual input points drain to more than one spring.
(iii) It is not unusual for the pattern of traced drainage lines to cross underground without any mixing taking place.
(iv) Because this technique uses particulate tracers, it is only successful where the underground flow regime is turbulent.

The second commonly used tracer technique is to introduce a fluorescent dye into the sinking stream and to monitor springs for its reappearance. Strongly fluorescent dyes can be detected at concentrations which are invisible to the naked eye by measuring the fluorescence of the water in a fluorometer. The intensity of fluorescence is proportional to the dye concentration. Recent developments have made it possible to employ up to to three dyes simultaneously in different stream sinks feeding the same spring. Dyes, being in solution, can be used to trace laminar as well as turbulent flows.

1.3: (i) *The calculation of underground velocity*

As well as discovering the pattern of underground flow from stream sinks to springs, it is of value to measure the velocity. The underground velocities are, by convention and necessity, obtained by dividing the straight line distance between the stream sink and the spring by the time taken before the arrival of the tracer. Whichever tracing method is used it is necessary to undertake repeated sampling at the springs to establish accurately the time of first arrival. With the spore technique this is obtained by collecting samples from the nets at known time intervals. With fluorescent tracers the detection of the first arrival of the tracer has been improved with the use of field fluorometers. For tests of short duration, say less than 24 hours, a field fluorometer can be used to monitor the spring continuously. For tests of a longer duration samples can be collected at pre-set intervals by means of an automatic water sampler for subsequent analysis.

The experiments described in the literature were undertaken under a variety of discharge conditions; in all cases the velocities are fast by comparison with groundwater velocities in non-limestone rocks. Repeated tests of particular established flow lines under differing flow conditions are not common, and in this respect the records from Malham are of particular interest.

1.3: (ii) *Dye budgets*

Fluorometric methods enable the amount of dye recovered at the springs to be measured. If the amount of dye injected into a stream sink is known and the dye reappears at more than one spring, it is possible to calculate the relative importance of each of the routes from sink to spring. This method of budgeting depends on two additional factors. Firstly, the dye used must be conservative, i.e. it is not lost within the system by chemical decay or absorption. Secondly, it is necessary to measure the discharge of all the springs at which the dye reappears. Only a small number of fluorescent dyes can be considered as truly conservative and there is little doubt that the best readily available dye in this category is Rhodamine WT.

A further extension of the dye budgeting methods takes into account the topology of the underground drainage network in relation to the form of the dye output at the spring. This is described by Brown and Ford (1971), Brown (1972) and Atkinson *et al.* (1973).

1.3: (iii) *Flood pulses*

An additional method of water tracing which does not involve the use of tracers in the conventional sense is known as flood pulse analysis. Such a pulse results from a storm or more conveniently may be artificially created by opening sluice gates or breaching a temporary (small!) dam. The pulse is observed at the stream sink and neighbouring springs monitored to establish where the pulse reappears. The method is best applied to simple systems where an artificial flood pulse is allowed to enter only one stream sink.

Flood pulse methods, however, are more important to an understanding of groundwater flow in limestone than simply as an alternative method of water tracing. The modern applications of the technique were first described by Ashton (1966) who pointed out that flood pulses will pass through conduits in the vadose zone at approximately the same velocity as in a normal stream, but will be transmitted instantaneously by displacement of water in phreatic conduits. Thus, if the flood pulse were tagged by the addition of a tracer, the arrival of the pulse at the upstream end of the phreatic portion of a cave would be marked by an increase in discharge at the spring, although it would not be until the tracer reappeared that the flood water itself could be said to have passed through the system. Clearly, the volume of the phreatic zone swept out by the flood water is given by the total volume discharged from the spring between these two times, provided no tributaries join the system within the phreatic zone. The shaded area marked A on Figure 1 represents this volume. The second area,

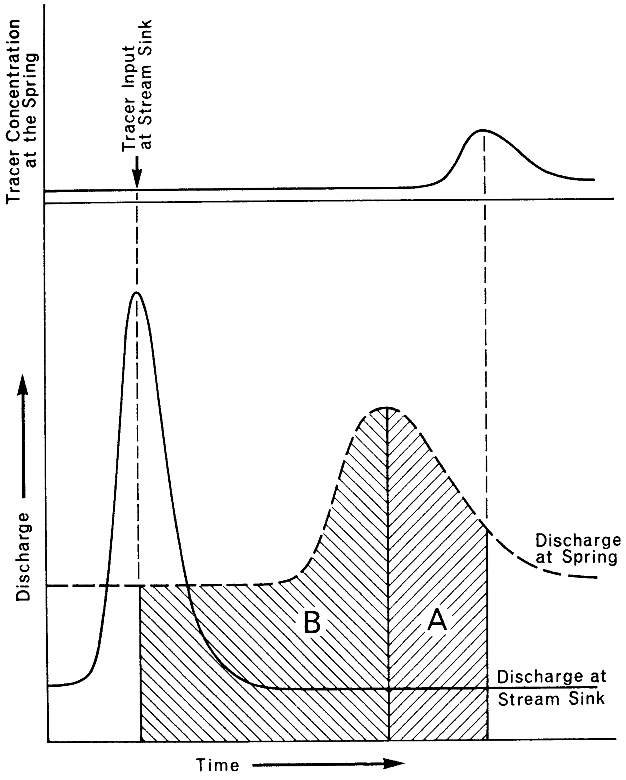

FIG. 1.

Diagram to show principles of analysis of water pulses.

marked B, indicates the volume of water displaced from vadose passages by the flood pulse, but this area gives a reliable estimate of the true volume of vadose passages only if either (i) all inlets to the system respond identically to flooding, or (ii) the tagged input pulse forms a known and large proportion of the discharge at the resurgence. Even then, the estimate of vadose volume is very rough and should be interpreted with caution. Ashton (1966) presents a full exposition of these principles which are elaborated by Brown (1972). Atkinson *et al.* (1973) describe their application to a natural flood in a cave system in Somerset.

2. The History of Water Tracing at Malham

Early water tracing in the Malham area occupies a well-acknowledged place in the limestone hydrology literature. The original aim was to trace the sources of water that feed the springs at the foot of Malham Cove (NGR SD 898642) and the springs at Airehead (NGR SD 902622). The Malham Cove water is known as Malham Beck and is joined by Airehead water to become the River Aire. The Airehead source consists of two distinct springs located a few metres from one another. The stream sinks most likely to feed the springs are Water Sinks (NGR SD 894655) and Smelt Mill Sink (NGR SD 882660). The location of these and other features is shown on Figure 2.

To illustrate the background of the water tracing an outline of the geology of the area is necessary. The geology is also shown on the map and cross-section in Figure 2. The map is based upon Garwood and Goodyear (1924), Hudson (1933) and O'Connor (1964) and the cross section on Howarth *et al.* (1900). The cliffs of Malham Cove, 80 m high, lie between the Middle and North Craven Faults. To the south of the Cove, the Malham Beck flows first across the Great Scar Limestones, crosses the Middle Craven Fault on to the "reef" limestones of Cawden, and then passes onto the Bowland Shales which unconformably overlie the limestone in a syncline beneath the village of Malham. The Airehead springs lie on the southern limb of this syncline, almost at the top of the limestone succession.

Malham Cove itself forms part of an escarpment to the north of which the land rises to an average elevation of 375 m above sea level, forming a bleak moorland at the foot of Fountains Fell. This moorland is traversed from east to west by the North Craven Fault. North of the fault is an inlier of Silurian slates, overlain by Pleistocene drifts, which by their impermeable nature support the waters of Malham Tarn. Farther to the north, slopes formed on Great Scar Limestone and Yoredale Series rocks rise to the summit of Fountains Fell (NGR SD 865716). The present extent of Malham Tarn is 61 hectares, but the natural lake was enlarged by the construction of a dam to raise the water surface in 1791. The overflow passes through sluice gates, flows southwards across the North Craven Fault and sinks into the Great Scar Limestone at Water Sinks (NGR SD 894655). Below the Water Sinks the Watlowes dry valley continues to the top of Malham Cove, and under exceptionally wet conditions the stream overflows down this valley, and has even reached the Cove on very rare occasions. A smaller stream flows across the Silurian slates to sink into the Great Scar Limestone at Smelt Mill, or "Streets" as some early accounts quoted in Tate (1879) call this locality (NGR SD 882660).

A general account of the local geology can be found in Waltham (1973), while more detailed descriptions and maps are given by Garwood and Goodyear (1924) and O'Connor (1964).

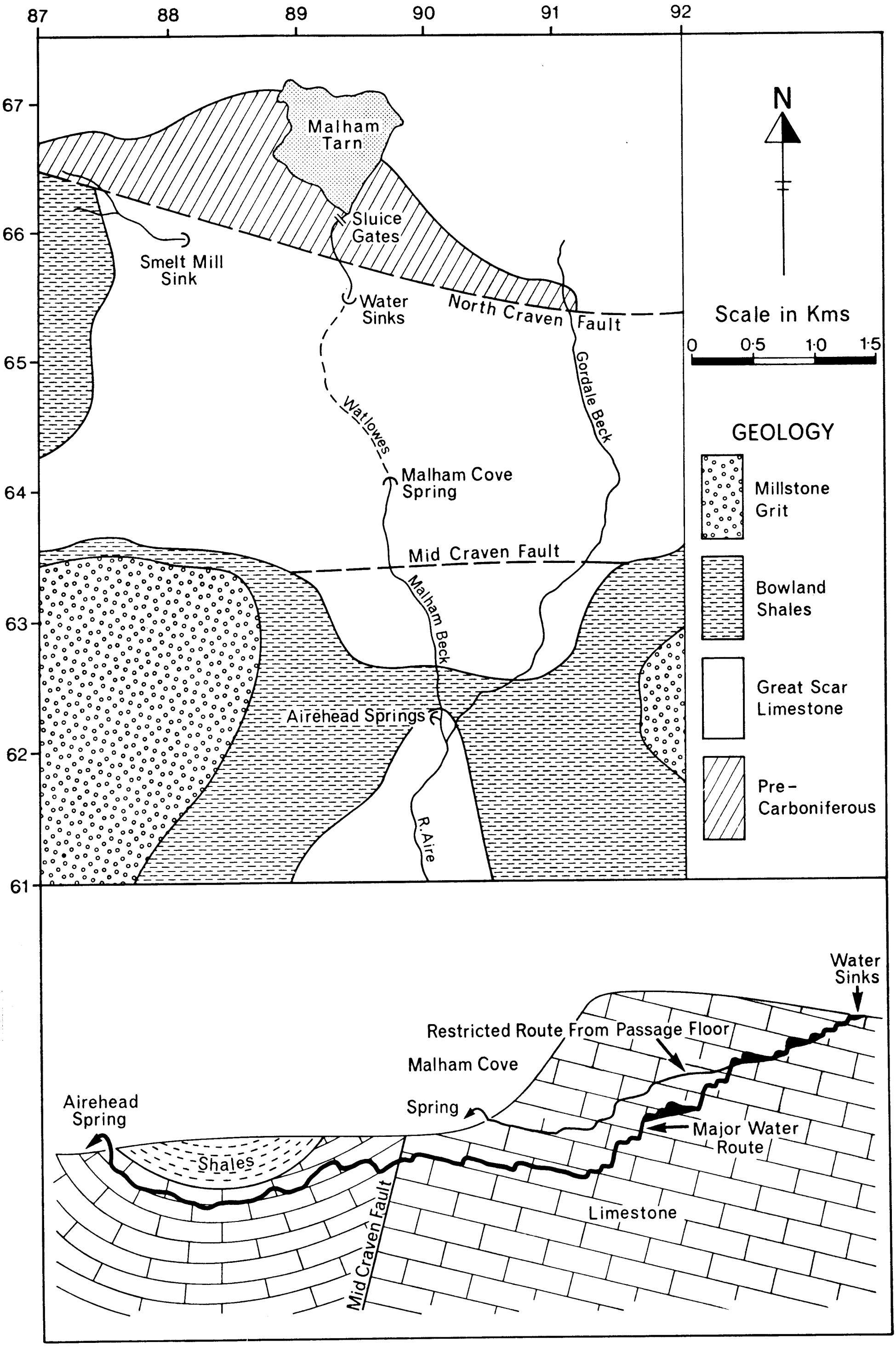

Fig. 2.

Geological map and section of the Malham area, showing structure and the authors' interpretation of the underground drainage system.

The first systematic attempts to demonstrate that water from Malham Tarn feeds the River Aire were made between about 1870 and 1879 by Walter Morrison, the owner of Malham Tarn Estate, and are reported by Tate (1879) who conducted his own experiments in the latter year. The early experiments in this period attempted to use various crude tracers (Table 1) which were all failures, but were followed by the successful use of flood pulse methods. It seems likely that Morrison's experiments were the first successful use of this method of water tracing anywhere. The sluice gates of Malham Tarn were opened and a pulse of discharge allowed to flow into Water Sinks. In all cases this resulted in an increase of the flow at Airehead Springs, demonstrating a connection from Water Sinks. Apparently conflicting results, were obtained at Malham Cove spring, which was affected by two pulses on successive days in 1879, but not in Morrison's earlier experiments. These results are set out in chronological order in Table 1 together with those of subsequent experiments.

Apart from an unsuccessful attempt by Thompson (1891) to use Fluorescein dye to trace the flow from Water Sinks, no further work was reported until 1900. In the previous year the Council of the Yorkshire Geological and Polytechnic Society appointed a Committee to investigate the underground waters of north-west Yorkshire. The work of the Committee began in 1899 and the results of experiments in the Malham area are reported by Howarth *et al.* (1900). Water pulses were again employed on three occasions at Water Sinks, with responses at Airehead which were similar to those observed by Tate and Morrison. In the first experiment, in June 1899, no effect was observed at Malham Cove spring, but in the second and third, in August 1899, increases were produced in its discharge. During that summer a variety of chemical tracers were introduced into both the Malham Tarn and the Smelt Mill sinks (see Table 1). By these means, Smelt Mill stream was shown to feed Malham Cove spring and Malham Tarn Water Sinks to feed Airehead with times of travel of 10–11 days. In addition, ammonium sulphate, which had been introduced into Water Sinks in June 1899, appeared in a trace quantity at the Cove spring, confirming the results of the water pulse experiments—that a connection existed between these two points, at least under some conditions. No further water tracing for Water Sinks or Smelt Mill Sink are reported in the literature until the work of the present authors which will be described below. The results of the nineteenth-century tests can be summarized as follows:

1. The water from Smelt Mill Sink was traced by chemical methods to Malham Cove but no trace was found at Airehead Springs;
2. Chemical tracers from Water Sinks established a strong connection to Airehead Springs and a weaker connection to Malham Cove;
3. Pulse methods established a clear link from Water Sinks to Airehead Springs with an irregular response at Malham Cove.

2.1: *The Pulse Problem*

In summing up the results of the experiments prior to 1899, Howarth succinctly states the major questions which still required an answer.

> "Why does the Tarn water flush Malham Cove sometimes and not always? Why does the Tarn water reach Airehead before Malham Cove, which is a mile and a quarter nearer? Why were the chemicals introduced so long in transit?

Table 1. *Summary of connections established by water tracing in the Malham area*

Person	Source	Methods	Sinks Tested	Effects at Springs	
				Malham Cove	Airehead
Morrison	Tate, 1879	Water pulse	W. S.	No effect	Increased discharge
Tate	,,	Water pulse	W. S.	Increased discharge after 2 h 10 min	Increased discharge after 1 h 25 min
Tate	,,	Bran, chaff	W. S./ S. M.	No effect	No effect
Tate	,,	Magenta dye	S. M.	No effect	No effect
Thompson	Thompson, 1890	Fluorescein (*c.* 500 gm)	W. S.	No effect after 3 h	No effect after 3 h
Y. G. P. S.	Howarth *et al.*, 1900	Water pulse June 1899	W. S.	No effect	Increased discharge after *c.* 2 h
Y. G. P. S.	,,	Water pulse Aug. 7 1899	W. S.	Increased discharge	Increased discharge
Y. G. P. S.	,,	Water pulse Aug. 26 1899	W. S.	Increased discharge	Increased discharge
Y. G. P. S.	,,	Fluorescein (*c.* 100 gm) May 1899	W. S.	No effect after 6 h	No effect after 6 h
Y. G. P. S.	,,	Ammonium sulphate (650 kg) June 1899	W. S.	Trace detected after 11 days	Strongly positive after 11 days
Y. G. P. S.	,,	Fluorescein (*c.* 1,500 gm) June 1899	S. M.	Green colouration after 10 days	No effect
Y. G. P. S.	,,	Sodium chloride (3,000 kg) July 1899	S. M.	Chloride detected after 11 days	No effect
Authors	—	Water pulse April 1972	W. S.	No effect	Increased discharge after 1 h 30 min
Authors	—	*Lycopodium* (4 kg) 1972	W. S.	Positive after 24–28·5 h	Positive after 13·5—24 h
Authors	—	Rhodamine WT (300 gm) 1972	W. S.	Trace detected	Positive after 25·5 h
Authors	—	*Lycopodium* (4 kg) 1972	S. M.	Positive after 2–6·5 h	Positive after 6·5—10 h
Authors	—	Water pulse July 1975	W. S.	Discharge increased slightly after 4 h 15 min	Increased discharge after 1 h 30 min
Authors	—	Rhodamine WT (300 gm)1973	W. S.	Positive after 20 h	Positive after 43 h
Authors	—	Pyranine (100 gm) 1973	S. M.	Positive after 22 h	Positive after 22 h

W. S. = Water Sinks, S. M. = Smelt Mill, Y. G. P. S. = Yorkshire Geological and Polytechnic Society

Are there any underground caverns between the sinks and the outlets?" (Howarth *et al.*, 1900, p. 11).

Kendall (in an appendix to Howarth *et al.*, 1900) attempted to answer these questions. He envisaged the flow from Water Sinks to Airehead as occurring in a zone of joints and master joints lying in a trough or "valley" in the water table. As shown in Figure 3, which is redrawn from Kendall's own figure 7 (Howarth *et al.*, 1900, p. 42) this trough is separated from a similar trough which is connected to Malham Cove spring. Kendall supposed that the effect of a water pulse would be to partially fill the trough in the water table in Valley no 1. in Figure 3. In dry conditions the ridge in the water table between the troughs ("the underground water-

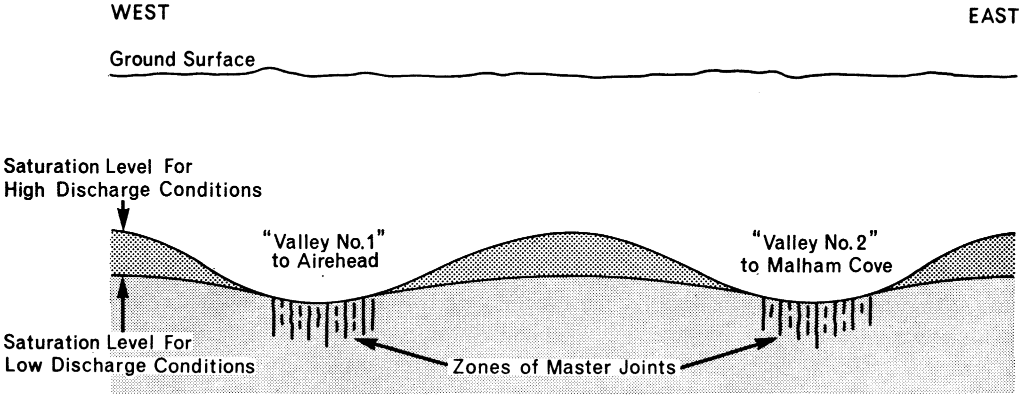

FIG. 3.

Diagram to show Kendall's interpretation of the underground drainage system of Malham. (Redrawn from Howarth *et al.*, 1900 p. 42).

shed") would be low and some of the pulse water would spill over it to affect Valley No. 2 which leads to Malham Cove spring. Under wetter, high discharge conditions, the ridge in the water table would be much higher and the volume of the pulse insufficient to overtop it. Kendall's explanation relies upon concepts of "normal" groundwater behaviour and he specifically dismisses the possibility of flow in conduits and "the hypothetical cave which has been supposed to lie beneath the limestone plateau at Malham Cove" (Howarth *et al.*, 1900, p. 44).

We consider that the variable effect of pulses at Malham Cove can equally well be explained in terms of conduit flow as by Kendall's hypothesis. In reaching this conclusion we took into account all the evidence, including a flood pulse interpretation of the nineteenth-century experiments along the lines shown in Figure 1. The nineteenth-century experiments were undoubtedly the most advanced of their kind, but the application of flood pulses other than as an additional tracing technique was not appreciated. However, the results of the experiments are so fully presented that it is possible to use the original data to gain additional information by applying more recent aspects of pulse wave hydrology.

3. RECENT WATER TRACING EXPERIMENTS

The present authors undertook two further water tracing experiments at Malham, in April 1972 and July 1973. The results of these experiments will be described separately, but the basic design was the same in both cases. Tracers were introduced into both Water Sinks and the Smelt Mill Sink, and were monitored at Malham Cove and at each of the two springs at Airehead (referred to as Airehead North and South). The *Lycopodium* spores were monitored using plankton nets as described by Drew and Smith (1969); to monitor the dyes their concentration in water samples was measured with a Turner Model III fluorometer. The discharge at the sinks was measured when the tracers were injected, using standard current meter techniques (Carter and Davidian, 1968). The discharge of the springs were also recorded by current meter, but several measurements were carried out during each test and the results related to the river level as recorded on a calibrated pole. Frequent readings of river level were made during the test, thus giving a more or less continuous record of discharge. On both occasions a pulse of water was released from Malham Tarn, over a period of one hour in 1972 and 2·75 hours in 1973. The discharges of the pulses were measured by current meter. Rainfall records during the tests were obtained from the meteorological station at Malham Tarn Field Centre (NGR SD 894673).

3.1: *Experiments 13–18 April 1972*

The first experiment was conducted between 13 and 18 April 1972, There was a single fall of 8·3 mm of rain in the evening of the 14 April, but otherwise no rain fell during the test (see Figure 4). The discharge at Airehead springs was 508 litres per second (l/s) at the time the tracers were injected on 14 April, and fell to 250 l/s on the 17th. The details of discharge at all sites are shown in Figure 4. The sluices on Malham Tarn were opened between 0945 h and 1045 h on 14 April, increasing the discharge from 250 l/s to 413 l/s. At 10.20 h three hundred grams of the liquid dye Rhodamine WT were added to the stream at the Tarn sluice. At the same time, the pulse was followed down the valley to Water Sinks and when it arrived there 4 kg of *Lycopodium* spores dyed with Saffranine were added. A similar quantity dyed with Malachite Green were injected into the Smelt Mill sink at 10.40 h. The first samples were taken from Airehead at 11.40 h and from Malham Cove spring at 12.45 h. Water samples were taken from Airehead every two hours throughout the test, separate samples being drawn from the South and North springs. At Malham Cove, samples were taken about every six hours. In addition small nylon bags containing activated charcoal granules were suspended in each spring for the duration of the test. If dye is present, even at concentrations smaller than a fluorometer can detect, it will be absorbed on to the charcoal and thus concentrated, and a qualitative assessment of its presence or absence can be made by washing the charcoal in warm methanolic potassium hydroxide and measuring the fluorescence of the resulting solution (Drew, and Smith, 1969; Smart and Brown, 1977, *in press*).

The pulse of discharge released at the Tarn produced an initial increase at Airehead at 11.15 h, increasing to a maximum of 565 l/s at 12.00 h, exactly one hour thirty minutes after the midpoint of the pulse reached Water Sinks. No response at all was observed in the water level at Malham Cove spring where a continuous watch was maintained for several hours (Figure 4). The tracer results are also shown in Figure 4, which displays the concentration of Rhodamine WT in the combined flow of both springs at Airehead and the relative concentrations of *Lycopodium* at each site in terms of numbers of spores trapped per hour. Dye was only recovered in detectable concentrations at Airehead, where it appeared at both springs. Although it was not detected in water samples at Malham Cove spring the charcoal detector bag showed a weak positive result on analysis after the test. Thus, a trace of dye reappeared at this spring, but its concentration never exceeded the detectable limit of 0·1 parts per billion (1 billion $= 10^9$). Saffranine *Lycopodium* spores from Malham Tarn were recovered from both South and North springs at Airehead (total 209) and in much smaller quantities (total 6) from Malham Cove spring. These results confirm those of earlier workers, but the times of travel are much faster being between 13·5 and 24 hours for the arrival of the first spores at Airehead and 25·5 hours for the arrival of the maximum dye concentration, compared with 11 days in 1899. The first spores arrived at Malham Cove after between 24 and 28·5 hours.

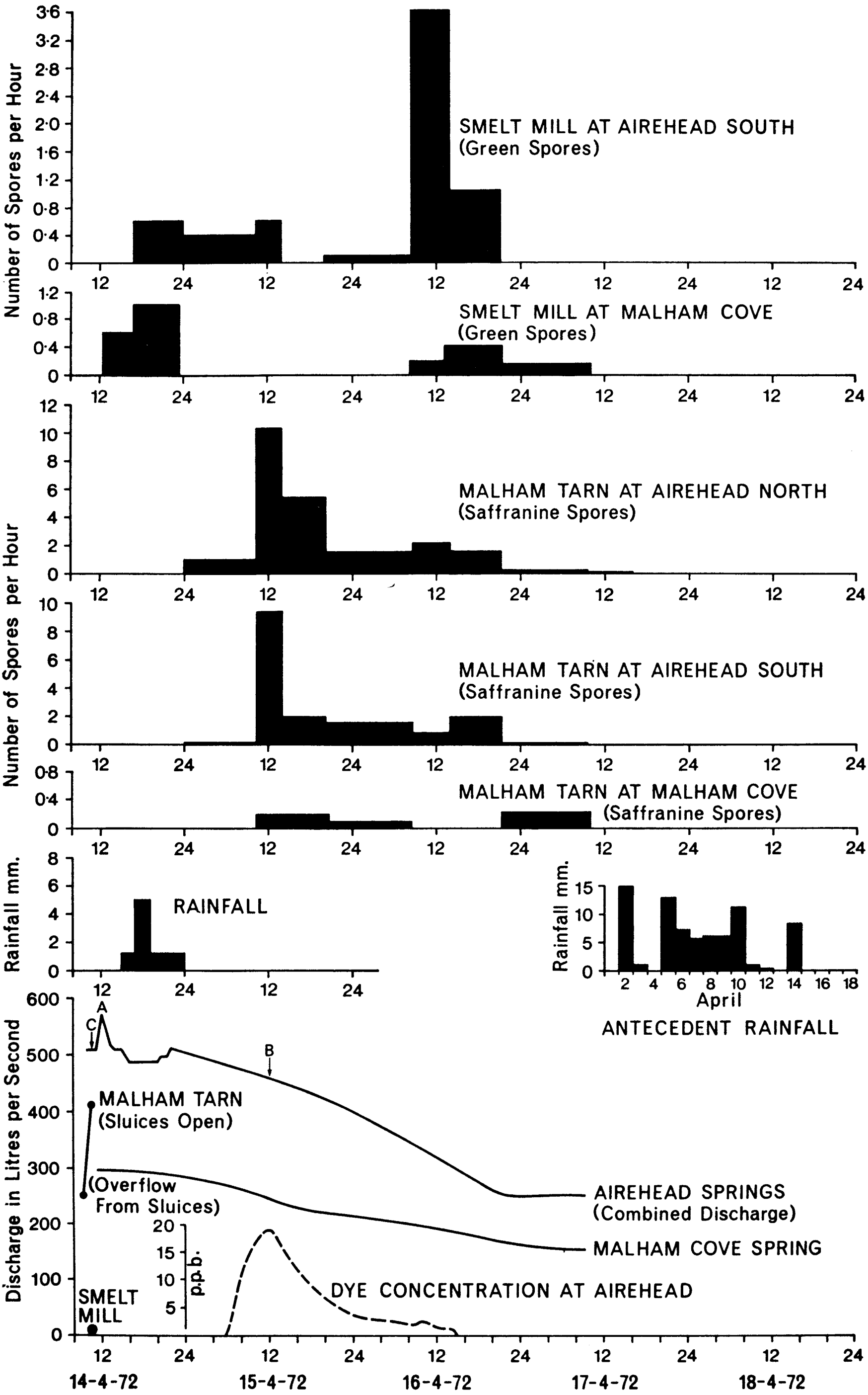

Fig. 4.

Discharges, precipitation and tracer concentrations at springs in April 1972.

The Malachite Green spores from Smelt Mill sink appeared at Malham Cove spring after between 2 and 6·5 hours, confirming earlier results. But green spores were also recovered from Airehead South in much greater numbers, the first arriving after between 6·5 and 10 hours. No green spores were recovered from Airehead North, indicating that the two springs are not fed by completely identical sources. This result differs from those of all earlier workers.

3.2: *Experiments 13–17 July 1973*

Discharge conditions were high in April 1972, and the experiment was repeated in July 1973 in order to investigate the system under low flow conditions. On this occasion the Smelt Mill stream was traced using 100 gm of Pyranine and the Water Sinks with 300 gm of Rhodamine WT. The tracers were injected at 12·15 on 13 July and at the same time the sluice gates were opened at the Tarn. Water samples were taken every few hours from both springs. The detailed results are shown in Figure 5, and indicate times of travel of 43 hours from Water Sinks to Airehead, and 20 hours to Malham Cove. From Smelt Mill, dye took 22 hours to reach both springs.

This test was conducted under lower flow conditions than those of 1972, with an initial discharge from Airehead of only 9 l/s. Rain fell during the course of the experiment as shown in Figure 5. The changes in discharge at Airehead did not mask the arrival of the water pulse from the Tarn. The initial rise began one hour thirty minutes after the sluices were opened and a peak of 98 l/s reached after four hours fifteen minutes. Discharge was not recorded at Malham Cove spring, but the level of the river was monitored using a pole marked in millimetres. A slight but definite rise in water level of 3 mm was recorded beginning at 16.30 h. The stream was four metres wide at this point, and it is considered that this rise represents the arrival of the water pulse from Malham Tarn.

4. DISCUSSION OF RESULTS

4.1: *Underground Connections and Velocities*

The results obtained in 1972 and 1973 confirm the earlier observations as regards the connections from Water Sinks to Malham Cove and Airehead. The connection from Smelt Mill to Malham Cove was also confirmed but in both the experiments the tracer from Smelt Mill also appeared at Airehead Springs.

The velocities of underground flow between the two sinks and the two risings are shown in Table 2. The values for the 1972 and 1973 tests are similar to those from other karst areas, while those of 1899 are somewhat lower. All the values should be regarded as under-estimates since the route actually followed underground will be considerably longer than the straight-line distances from sink to spring which were used in the calculations. From Table 4 it can be seen that both 1899 tests were undertaken under extremely low flow conditions which would, to some degree, account for the low velocities. There is little doubt that all the velocities obtained in 1972 and 1973 indicate turbulent flow conditions but in 1899 laminar flow conditions may possibly have occurred. For comparative data and methods of calculation see Smith *et al.* (1976).

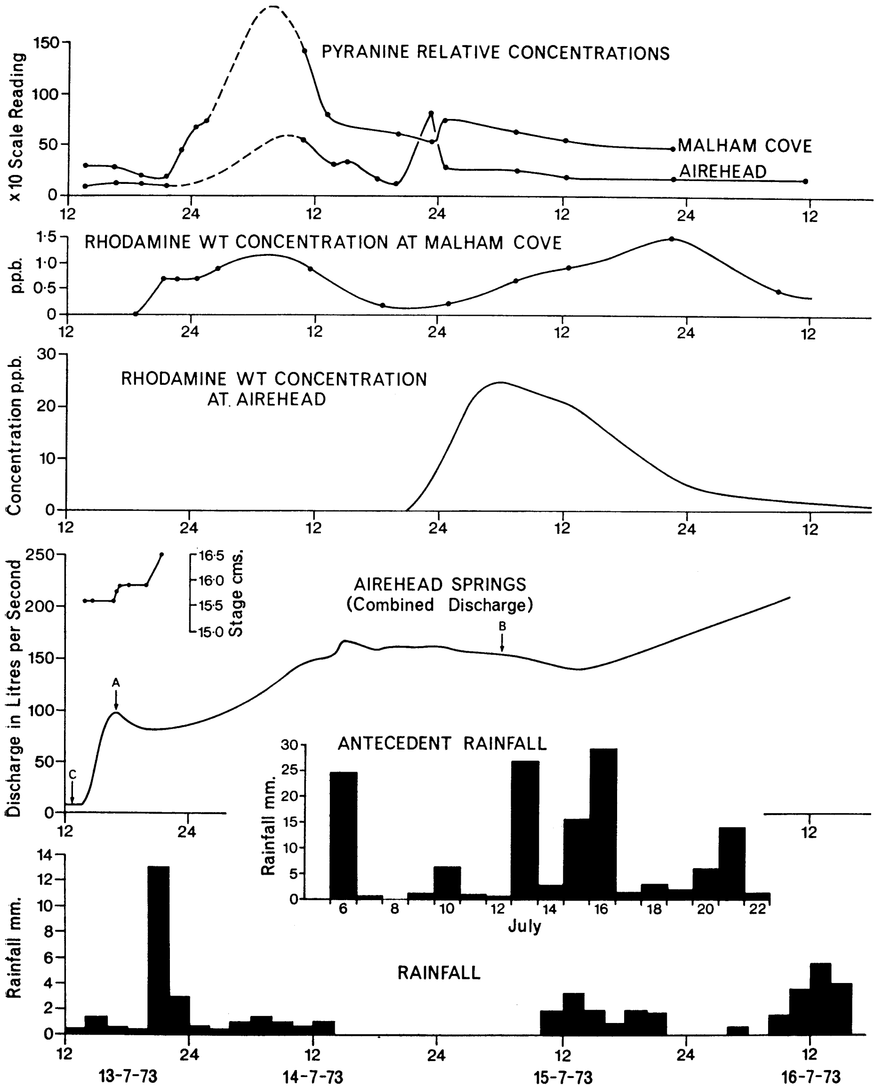

FIG. 5.
Discharges, precipitation and tracer concentrations at springs in July 1973.

4.2: *Pulse wave analysis*

The underground drainage systems of the Malham area are especially suited to the combined use of water pulses and tracers, as the sluices on Malham Tarn allow pulses to be generated at will. The method was outlined in the first part of this paper. For the 1972 experiment (Figure 4) the volume of phreatic passages is given by the total discharged volume between the peak of the pulse at Airehead (point A) and the arrival of the peak dye concentration (point B). This volume is 42,300 m^3. The peak discharge of the pulse at Airehead was used in the calculation because the dye was injected at exactly the midpoint of the input pulse at Malham Tarn. The volume of water in vadose passages connected with the Water Sinks can be estimated roughly

Table 2. *Velocities of flow between sinks and springs in the Malham area*

	1899	1972	1973
			(ALL FIGURES IN KM/DAY)
Water Sinks to Malham Cove Spring	0·15	1·4	1·7
Water Sinks to Airehead Springs	0·31	2·7	1·9
Smelt Mill Sink to Malham Cove Spring	0·26	9·8	2·9
Smelt Mill Sink to Airehead Spring	—	10·8	4·6

by finding the proportion of the Airehead discharge which is attributable to flow from the Sinks between the time the dye was injected (point C) and the arrival of the peak of the discharge pulse (point A). Since the discharge from the Tarn before the experiment was 250 l/s and that from Airehead 508 l/s a constant flow of 258 l/s from other tributaries to Airehead can be assumed. Thus, the flow from the Tarn increased in rate from 250 l/s at point C on Figure 4 to 278 l/s at point A, representing a volume of 1,400 m^3.

The calculations based upon the results obtained in 1973 are similar to those just outlined. The small discharge from Water Sinks to the Cove spring was neglected. The volume of phreatic passage was 17,600 m^3 and of vadose passage 640 m^3. The discrepancy between these and the 1972 figures prompts a re-examination of the 1899 data given by Howarth *et al.* (1900) who collected sufficient data for a rough pulse analysis. The base discharge from Airehead in June 1899 was 5·25 l/s (100,000 gals/day) and the chemical tracers took eleven days to pass through the system, indicating an approximate total volume of 5,000 m^3 (1·1 million gallons). Thus, there appears to be a systematic relationship between the calculated volume of the system and the discharge through it, as indicated in Table 3.

Table 3. *Discharges and calculated volumes at Airehead Springs*

Date	Average discharge during passage of tracer	Phreatic volume	Vadose volume	Total volume
June 1899	5·25 l/s	—	—	5,000 m^3
July 1973	131· l/s	17,600 m^3	640 m^3	18,200 m^3
April 1972	500· l/s	42,300 m^3	1,400 m^3	43,700 m^3

The explanation of the changes in vadose volume described above presumably lies in greater channel storage at higher discharges but the variation in calculated phreatic volume is harder to explain. One possibility lies in the synclinal geological structure between Malham Cove and Airehead. Here the groundwater in the Carboniferous Limestone is probably confined by the overlying Bowland Shales. White (1969) and Palmer (1975) describe how caves formed under shallowly confined conditions usually consist of a three-dimensional network of densly interconnected passages. Such a network in the confined section of the Malham drainage system could provide the explanation for the variation in calculated phreatic volumes as follows. The amount of lateral mixing (i.e. in a plane perpendicular to the general direction of flow) is likely to depend upon the degree of turbulence and the velocity, which both in turn depend upon the discharge. Thus, at low discharges the dyed water will sweep out only a small proportion of a network of solutionally widened fissures in the confined beds, following a relatively direct route from the point of entry to the exit. At higher discharges, the lateral mixing will be greater, dyed water will spread further into the recesses of the system, displacing the water already there, and the apparent volume will be greater.

It may be concluded, therefore, that the water flowing from Malham Tarn Water Sinks to Airehead initially follows normal cave passages with turbulent flow, but on reaching the confined section beneath the Bowland Shales it probably enters a three-dimensional network of phreatic cave passages and solutionally widened fissures in which flow may sometimes be laminar under low discharge conditions.

4.3: *The Connections between Airehead and Malham Cove Springs*

One of the more mysterious results of all the water tracing experiments is the variable response shown by Malham Cove spring to water pulses from the Tarn. Table 4 shows the occasions on which the pulses produced an effect on the discharge at the Cove. The rise in discharge is usually very small compared with that at Airehead. As Table 4 shows, whenever tracers and water pulses have been employed simultaneously a tracer connection has always been established between the Tarn and the Cove spring, even when water pulses produced no effect. Thus, a flow of water undoubtedly passes from the Water Sinks to the Cove, but its observed effect upon the discharge there is variable. At this stage it should be mentioned that the Cove spring and the Malham Beck are difficult sites at which to measure discharge accurately and much depends upon detecting a very small rise in water level (e.g. only 3 mm in 1973). Kendall's hypothesis to explain the variable effect of the pulses has already been discussed and was linked to variations in the position of the water table. Against this hypothesis, and in particular the conclusion that conduits play no part in the flow, are ranged the new evidence of very rapid flow velocity and the sharp nature of the discharge pulses at Airehead which rise and fall on emerging from the system almost as rapidly as they do on entering it. These

Table 4. *Connections between Malham Tarn Water Sinks and Malham Cove Spring*

Date	Discharge at Airehead before water pulse	Tracer connection	Water pulse connection
June 1899	5·25 l/s	Trace of ammonium sulphate	No effect
Aug. 1899	"very low"	Not determined	Increased discharge
April. 1972	508 l/s	Trace of Rhodamine WT, Positive *Lycopodium*	No effect
July 1973	9 l/s	Positive Rhodamine	Small increase in discharge

phenomena indicate concentrated, turbulent flow which can only be envisaged as occurring in conduits similar to those which have been widely reported from other limestone areas. The results of the water tracing can be explained by a conduit-based model, in contrast to Kendall's hypothesis, as follows. A major conduit leads from Malham Tarn Water Sinks to Airehead. Suppose that a minor conduit branches from it to Malham Cove spring and that flow down this passage is restricted in at least one bottleneck. The maximum flow which can pass the bottleneck is small and is often reached under wet conditions. Thus, if a water pulse is passed into this system when discharge is already above the limiting value which the bottleneck can freely transmit, no effect will be produced at Malham Cove spring. When the initial discharge is low, there will be spare capacity in the bottleneck and a water pulse will be detected at the Cove. Under all conditions, however, some water does pass the bottleneck and this should be reflected in the consistent recovery of relatively small amounts of tracers at the Cove spring. The higher velocities due to increases in pressure at the bottleneck are not thought to affect these conclusions significantly.

A consequence of this hypothesis, and one by which it may be tested, is that the tracer which is recovered from the Cove should be a higher proportion of the total when the initial discharge through the system is low, because under low flow the bottleneck conduit will take a larger percentage of the flow from Water Sinks. To test this, we calculated the amount of dye tracer recovered at each spring by multiplying the discharge by the concentration of dye and summing the values over the period during which the tracer emerged. The dye concentrations can be determined with an accuracy of ± 1 per cent but the errors in discharge measurements may be as high as ± 20 per cent. Applying this procedure to Airehead in 1972 shows that nominally 120 per cent of the 300 gm of dye injected at Water Sinks emerged at Airehead. Only a trace was recovered from the charcoal detector at Malham Cove, where the concentrations in the spring water were below the detectable limit of 0·1 ppb. The ratio of the peak dye concentration of 19·2 ppb at Airehead to this detectable limit of 0·1 ppb which was not exceeded at Malham Cove suggests that less than 0·5 per cent of the water from the Tarn emerged from the Cove spring in this experiment. The magnitude of this ratio is confirmed by the fact that 209 Saffranine *Lycopodium* spores were recovered from Airehead, and only 6 from Malham Cove spring, suggesting that about three per cent of the Tarn water emerges at the Cove.

Under the lower discharge conditions of July 1973, a much larger proportion of dye emerged from the Cove. At Airehead, a calculated 84 per cent of the 300 gm of Rhodamine WT was recovered indicating that a probable 16 per cent emerged at Malham Cove. Although discharge was not accurately recorded at the Cove, a rough calculation using the estimated discharge and measured dye concentrations suggests that these figures are correct. Thanks to the participation of larger numbers of observers, discharge records at Airehead were more accurate in 1973 than in the previous year, so that the agreement of figures is probably not fortuitous.

These dye-budgeting exercises seem to confirm the conduit-flow hypothesis outlined above, rather than the water-table hypothesis of Kendall. They suggest that a cave system does indeed exist beneath the limestone plateau at Malham Cove, a suggestion which is at least partially confirmed by the Cave Diving Group who have shown that the Cove spring issues from an underwater passage at the foot of the cliffs, which has been explored upstream for 50 m (Cave Diving Group, 1971, 1970, 1976).

4.4: *Conclusion*

In the light of the new data provided by the recent experiments, we suggest the following answers to the four questions posed by Howarth in the passage quoted above. It may be stated first that definite connections exist between Water Sinks and both Malham Cove and Airehead, with a more restricted connection with the Cove. The flow between these points is normally rapid and turbulent and is confined to conduits. A diagrammatic representation is given in the section in Figure 2. Thus, underground caverns can be said to exist between the sinks and the outlets, though not all need be large enough for a man to enter. Parts of these caverns are flooded, particularly those confined beneath the Bowland Shales and close toMalham Cove spring. The flooded sections transmit pulses more or less instantaneously, whereas the chemicals which mark the actual passage of the water take much longer to traverse them. Thus, the long period taken by the chemicals in transit is a measure of the volume of the water-filled sections of the caverns.

The Tarn water will flush Malham Cove only when conditions are right. Either the initial discharge must be very low or the water pulse must be very large for the bottleneck which is presumed to exist between Water Sinks and the Cove to be passed by a pulse large enough to be detected at the spring. Finally, it may be speculated that pulses take longer to reach the Cove than Airehead because a greater proportion of the course of the latter is water-filled (see Figure 2). Thus, in spite of the greater distance pulses are transmitted more quickly to Airehead.

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